Performance-based methods for masonry building rehabilitation using innovative leaching and hygrothermal risk analyses

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Abstract

The design and selection of a retrofitting solution can be carried out through performance-based methods (according to constructive materials behaviour, hygrothermal and occupants' behaviour or climatic conditions) as an alternative to the deem-to-satisfy approach. The future likelihood of saturated conditions in masonry building fabrics is increased by the consequences of climatic changes, enhancing the need of selecting adequate solutions for buildings retrofitting. As it was intended to propose the optimal solutions for the preservation of a Portuguese convent, major issues such as the high level of relative humidity inside the building and the leaching phenomenon of the mortar joints between bricks masonry were taken into account as a potential degradation causes. In situ inspection was made together with the analysis of the existing documentation regarding the building. The selection of the best retrofitting measures was supported by innovative leaching and hygrothermal risk analyses using probabilistic approaches. The probability of leaching of the mortar joints is minimised if NHL5 mortars are used for re-pointing when compared to NHL2 or NHL3.5 mortars. Regarding the hygrothermal performance of the building, indoor comfort increases 10% by increasing the Moisture Buffering Value of the indoor surface using eco-efficient earth plasters.

Keywords: Heritage; climatic changes; leaching; hygrothermal; performance-based design; Humidity buffering; bio-based.

1. Introduction

The conservation and refurbishment of historic heritage and old buildings has been in the world and European agenda for many years. There is now a sense of awareness of the importance of built heritage preservation as its cultural value defines a unique and distinct identity [1, 2]. In some cases it is considered the need to find new socio-economic uses for heritage buildings in order to maintain them active and sustainable by adapting these buildings to a new function when the original is no longer required and by protecting them to future climatic changes [3; 4]. Such active conservation strategies aim to achieve a better integration of the heritage within its surroundings, including social aspects, but also to guarantee the use and conservation of the architectural heritage – because many abandoned buildings cannot be maintained and preserved as they were.

This paper analyses the conservation and rehabilitation approaches for the Convent of Madre de Deus (Mother of God) of Verderena in the city of Barreiro, Portugal, built in the sixteenth century by the Capuchin Franciscans. Nowadays the convent is partially used as a public library and will be used also by the University for the Third Age. In order to upgrade the building, interventions where carried out during the 1970´s and 1990's. However, such interventions were insufficient and unsuitable given the degradation level of the building. The degradation occurred mainly in the external and internal envelopes (walls and roofs) of the convent [1], due to the inadequate indoor environment quality, high levels of relative humidity and leaching phenomenon of the mortar joints between bricks masonry.

Old buildings can be built of thick massive masonry walls of porous and very absorbent materials. These buildings are frequently affected by salt decay problems that require appropriate interventions to solve, or at least minimise, such problems. However, professionals involved in the conservation of old buildings claim that salt damage features are often worsened, rather than minimised, after conservation interventions, even when they were specifically carried out to solve salt decay problems. This common statement refers essentially to an increase of surface damage [5; 6].
The introduction of materials that are incompatible with the pre-existing ones, such as cement mortars and low permeable paints that hinder moisture drying and evaporation, affect not only the aesthetic but also the

environmental comfort. At a medium term those materials will affect the resistance of the load-bearing structure. When the external rendering and interior plastering of the masonry structure is compromised, water penetrating dampness and diffusion is enabled. High moisture content inside the wall not only contributes to increase the appearance of fungus and biological colonisations but also to worsen capillary rise and cyclic salt crystallization and dissolution. Subsequent weakness of the walls´ resistance will occur due to the development of tensions, loose of cohesive properties and leaching phenomena of the original materials - as the case of mortars.. For that reason the repair, maintenance and sustainable consolidation of old mortars is very important when it comes to built heritage preservation [6]. Well-conceived interventions are needed for the preservation of all the values present, namely those of cultural, historical, economical and social nature. Developing maintenance view of the repair of buildings towards sustainability was extensively studied by Kayan et al [7]. The added value of their maintenance approach for historic masonry buildings relays on the carbon cost of repairs contextualised within the longevity of the materials and its embodied carbon that consequently allows rational appraisal of repair and maintenance options.

In climate research, emissions scenarios are used to explore how much humans could contribute to future climate change given uncertainties in factors such as population growth, economic development and development of new technologies. Scenarios have long been used by planners and decision makers to analyse situations in which outcomes are uncertain. Models for the future climate in regions such as in Portugal or UK, for instance, suggest more intense rainfall which will result in the materials used in masonry structures being saturated for longer periods and, therefore, at higher risk of binder leaching and consequent deterioration [8; 9].

Findings of the IPCC Fifth Assessment Report (AR5) are based on a new set of scenarios called Representative Concentration Pathways (RCP) [10]. According to RPC 4.5, which is a scenario consistent with a future with relatively ambitious emissions reductions, it is expected an increasing rainfall associated with climate change in Portugal. Figure 1 presents the predicted climatic changes in terms of precipitation increase expected in Portugal until 2100.

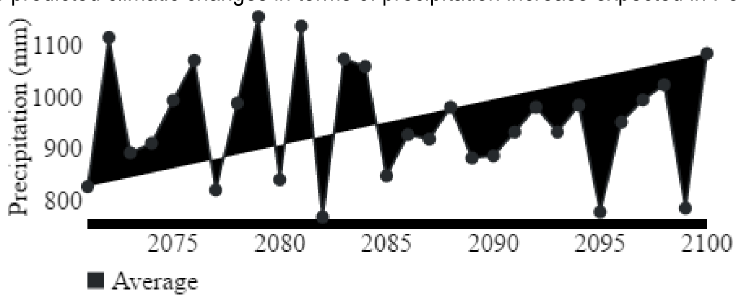


Figure 1 – Rainfall increase expected in Portugal until 2100, according to RPC 4.5 scenario [9].

In masonry structures, high moisture contents can contribute to binder leaching due to in calcium-based materials [11; 12], which means that the implication in the structural integrity of masonry becomes evident. McKibbins [13], for instance, suggested that saturation of porous masonry materials is a major problem in traditional arch bridges, with increased, lime leaching and creation of secondary porosity leading to washout of fines, increased susceptibility to freeze thaw cycling, frost attack and concentration of stress in localised regions.

Soluble components within the mortar may dissolve and migrate through the material to be re-deposited within the pores, in construction voids, or as efflorescence on external faces of masonry. The binder components vulnerable to dissolution are mainly portlandite (calcium hydroxide, $Ca(OH_2)$) and calcite (calcium carbonate, $CaCO_3$) [14; 15]. Less hydraulic lime binders should be more susceptible to dissolution, particularly in saturated, cold conditions because the solubility of both $Ca(OH)_2$ and $CaCO_3$ increases as water temperature decreases [16]. According to Forster [8] less hydraulic limes have a higher proportion of $Ca(OH)_2$ and are likely to be more reliant on carbonation for hardening as they contain a lower proportion of the hydraulic components.

The design and selection of a retrofitting solution for the convent of Madre de Deus of Verderena can be carried out through performance-based methods (according to constructive materials behaviour, hygrothermal and occupants' behaviour or climatic conditions) as an alternative to the deem-to-satisfy approach, i.e. definition of the quantities of its constituents. Major issues such as the high level of relative humidity and the leaching phenomenon of the mortar joints between bricks masonry were taken into account as a potential degradation cause. The building evaluation took into account the existing documentation and in situ inspection regarding the building typology, constructive system, materials and previous construction works. The selection of the best sustainable retrofitting measures was supported by innovative leaching and hygrothermal risk analyses using probabilistic approaches.

The conceptual basis of a probabilistic-based approach is to ensure that the required performance - controlling the leaching depth to ensure higher masonry durability and safety - is improved throughout the intended mortar and building hygrothermal behaviour. The methodology for probabilistic analysis and design in this paper is built on several state-of-the-art principles [17-21] to calculate and analyse the output uncertainty.

2. Building typologies

The building was constructed during the sixteenth, seventeenth and eighteenth centuries with the resource to traditional materials and systems. The main load-bearing structure consists of stone masonry walls. The walls are built using local field limestone and lime mortar. Stone blocks used in corners, door and window frames are dressed, whereas stone blocks (rubble stone masonry) used in the main wall are rough, unhewn, laid irregularly and set with lime mortar. In portholes, windows and doors, structure reinforcement is ensured by discharging arches built of massive clay brick masonry. Originally, rough masonry would be rendered and plastered with lime mortar and painted with white lime wash [1]. In old buildings, this technique allows moisture to freely move through the walls and evaporate at the surface, keeping it dry [22; 23]. Simultaneously, protects the plastered masonry from cyclic hygrothermal changes due to different uses along the periods of time.

Ground flooring is riprapped and fastened with mortar and then paved either with stone slabs or rustic clay tiles, according to the use or the nobility of the room. Ceilings are barrel vaults made of brick masonry. When the convent was built, the intrados of the vault was plastered with lime mortar and lime washed. Nowadays, some of the vaults are unplastered, showing its structure [24] and loosing hygrothermal protection. In order to construct the second story, above the structure of the vault, the spandrel would have been filled with a mixture of sand, brick fragments and rough stone set in lime mortar and then flooring would have been laid down. In the exterior areas, such as the terrace, the floor is in either rustic clay tiles or stone slabs whereas in the dorm room, the most likely solution would be hard wood flooring installed perpendicularly to bearers placed over the vault spandrel [23].

The roof is ridged, double sloped, constructed with timber roof truss structure. Roof covering is assured by ceramic tiles displayed in the Monk and Nun style, also known as priependach, where two arched imbrex tiles are used. Carved limestone is used in classic architectural elements in the interior, like a sculpted washbasin and a sundial [22; 23; 25].

3. Building anomalies assessment

3.1. The building usage

To avoid the degradation of the convent itself and the cityscape it belongs to, a new use for the building is desirable in order to supply finances for its maintenance and conservation. Therefore, the consideration of maintenance and moisture ingress must be highlighted and well-conceived interventions are, consequently, needed for the preservation of all the values present, namely those of cultural, historical, economical and social nature.

Concerning the convent of Madre de Deus of Verderena, the main goal was to preserve the originality of spatial and volumetric organization of the convent. It was intended to adapt the rooms organized around the cloister, specifically to change the dorm rooms to a library (1st floor of the building) for the local citizens and the ground floor to be used by the University of the Third Age (U3A) organization. The objective was to provide life-enhancing and life-changing opportunities to retired and semi-retired people. Figures 2 and 3 show those selected areas.

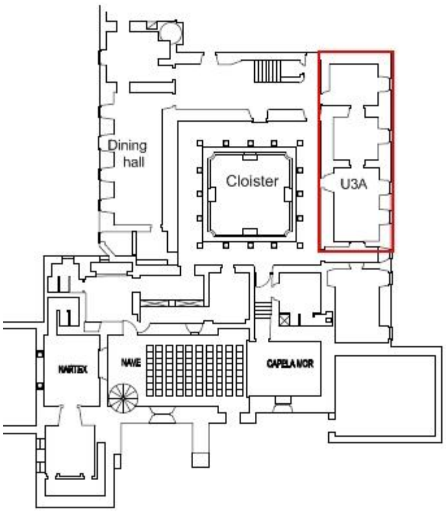


Figure 2 - Selected area to implement the U3A (ground floor of the Convent).

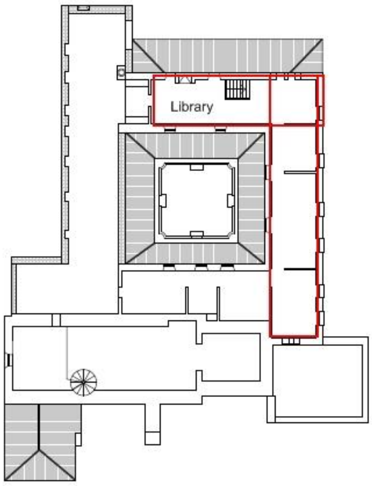


Figure 3 - Selected area of the library (1st floor of the Convent) already in use.

3.2. Building inspection and evaluation of anomalies

The convent inspection was carried out taking into account several factors such as geometry, structural characteristics, physical and chemical characteristics of all constituent elements from a particular (the library and the U3A areas) and a global point of view (the entire building). The evaluation also included the analysis of previous construction works – and respective drawings from the execution phase - that had occur in the Convent (namely in the 1970's and 1990's) [1; 26; 27]. This characterization was crucial for the establishment of a correct diagnosis.

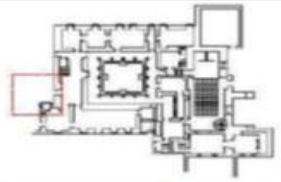
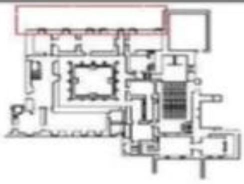
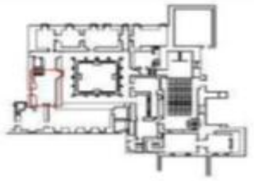
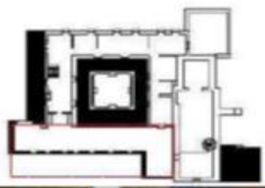
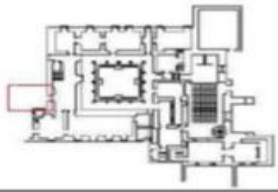
Some nonconformities between drawings and previous construction works were found, namely concerning the absence of some walls - that are not observed in situ but are mentioned in drawings. According to the construction specifications, it was also prescribed the use of cement mortars for plastering and rendering repair and replacement. Thus, even before the visual inspection of the building it was expected to find a significant number of anomalies associated to this implementation.

The degradation level evaluation of the external and internal envelopes (wall and roofs) of the convent was based on historical investigation (documents), visual survey, laboratory testing and interviews to the asset managers from local authorities and to the person in charge of the building management. Given the importance of authenticity issues, as far as architectural conservation is concerned, only non-destructive or slightly destructive tests were adopted.
The historical investigation previously made to the Convent enabled to understand the adopted techniques used in oldest interventions and the characteristics of materials used on those restoration works (in particular concerning the use of new materials) and their compatibility with existing materials [1]. Figure 4 presents the general view of the convent and its orientation.

Figure 4 - General view of the convent and its orientation. The blue rectangle shows the main area where is the library (1st floor) and where the U3A (ground floor) will be implemented [28].

The following anomalies could be highlighted from the visual inspection (Table 1):

Table 1- Main pathology observed in the Convent.

A Wall, external rendering, paints and stonework **Observed damage** Degradation, cracking and mortar disintegration Shoaling of the applied paint Efflorescence Biologic colonization Dysfunctional water flow system Vandalism	 
B Wall, external rendering and paints **Observed damage** Shoaling of the applied paint Degradation, cracking and mortar disintegration Biologic colonization Rising damp Vandalism	 
C Unplastered vault near the library **Observed damage** Degradation of the the mortar joints between bricks Water infiltration	 
D Terrace above library access **Observed damage** Dysfunctional water flow system at the terrace Water accumulation due to small inclinations of the floor	 
Problems in the water roofing system below ceramic tiles and near the door Inexistence of expansion joints at the ceramic tiles floor	 
E Masonry wall **Observed damage** The main structural damage exhibited by the masonry consists of diagonal cracks. Those cracks intercept the cross section of the platband above hidden masonry arch	  

Originally the vaults of the convent were covered. Currently some of them are unplastered, showing their structure, namely the one presented in situation C – Table 1. In this situation, some salt crystallization and leaching phenomena of the mortar joints between brick masonry could be observed (Figure 5).

Figure 5 - Presence of salts and leaching phenomena of the mortar joints of the brick masonry vault confirms the migration of binder from the original lime mortar.

The major benefit achieved by covering a vault with a plaster is the reduction of moisture present inside the masonry structure and particularly to stabilize the moisture content in the masonry even with different indoor cycles of relative humidity [29; 30]. The presence of water and its movement inside the pore network of mortars are among the biggest causes of their degradation [29, 31, 32]. In fact, depending on the conditions of temperature and humidity, water in both vapour and liquid state can allow freezing-thawing phenomena (in cold climates) and can favour the entry and the transport of salts which crystallize and dissolve inside the material matrix, namely the joint mortars. Therefore, it will cause the reduction of mortar mechanical strengths and adhesion to the masonry, whenever the RH decreases or increases from the salt hygric equilibrium level (what happens cyclically and very frequently with time).

Leaching phenomena presented in this convent probably occurs not only due to the extended water presence and infiltration from the terrace above the vault (situation D - Table 1), but also due to the lack of protection of the vault structure enabling the ceramic elements and the lime mortar from the joints to be directly affected by indoor hygrothermal conditions. This exposure to several cycles of different relative humidity (RH) could affect the lime mortars microstructure, leading to a decrease of adhesion and mechanical strength with time [24, 31, 33, 34].

Binder leaching has been little studied, however, the work of Forster et al [8,35] goes some way to rectifying this situation since they quantifies the rate of deterioration in uncarbonated and carbonated lime mortars.
The extent to which binder dissolution occurs in masonry buildings and its impact on lime mortar has not been enough studied, meaning that even if the rate of deterioration is extremely slow, the risk could be high in old structures, such as the historic ones, with a possible history of extant leaching. The previous situation, plus with the increasing of the impact of climatic changes, results in higher risk of binder leaching and consequent deterioration, which justifies a deeply analysis regarding the selection of the best mortar composition for repointing. Gaitero et al. [36; 37] and Berra et al. [38] reported the beneficial effect of ultra-fine particles of pozzolanic silica on the leaching and consequent deterioration.

Arizzi et al. [30] studied the durability of lime based mortars to be used as rendering materials in conservation interventions. To study the effect of ageing on the properties of these mortars, they have been subjected to accelerated weathering, by simulating the extreme atmospheric conditions (of temperature and relative humidity) which occur during 1 year in a city at South of Spain. The damage caused by rain and freezing–thawing cycles has also been studied by simulating rainfall and cycles with low temperatures. It has been found that mortars are much more resistant to salt deposition than to salt capillary absorption because the former only produces superficial decay whilst the latter generates internal cracks. Layer detachment can cause a lack of adhesion between the mortar surface and the masonry material (brick, stone) in joints or on the surface.

Problems in the terrace flat roof water proofing system of the convent and on its own positioning under ceramic floor tiles lead to water infiltration and damage of masonry walls and vault (situation D - Table 1). The lack of pending at the terrace able to drain rainwater for collection devices has serious consequences on the building functioning, namely in the structural performance of the vault mentioned in Situation C - Table 1, where water infiltration occurs leading to leaching phenomena of the mortar joints of the brick masonry vault.

Besides that, the previous construction works made in the 90's at the terrace, with the construction of a new cement based mortar layer and placement of the ceramic floor tiles (Figures 6 and 7) at the top of the hidden masonry arch increased the weight above this structural masonry, leading to crack evolution. This set of cracks could represent significant danger and a pre-collapse situation (situation E – Table 1) [1, 24].

Figure 6 - Terrace covering with ceramic roof tiles. Water accumulation due to insufficient slope of the terrace floor.

Figure 7 - The inexistence of expansion joints at the ceramic tiled floor leads to its fracture and to the cracking of cement based mortar layer under tiles, contributing for inefficient roof water proof and therefore leading to leaching of the mortar joints between brick masonry vault.

4. Selection of mortar composition for the leaching phenomena minimisation

Since the convent is subjected to a severe leaching phenomena and the structural integrity of masonry may be dependent on that, it was necessary to find the best re-pointing solution for the vault, compatible with the existing masonry materials. Therefore, different natural hydraulic lime mortars where studied (NHL2, NHL3.5 and NHL5) and the optimum solution was selected in face of its physical and chemical compatibility with the existing lime materials.

According to Banfill et al [35], the reductions in strength for carbonated mortars are less marked than for uncarbonated mortars. In their extensive study, uncarbonated mortars lost 96–99.5% of their compressive strength over 169 days [8] and the carbonated mortars lost 73–91% over the same period. Since carbonated mortars are more resistant to leaching than uncarbonated mortars, the following probabilistic models were only developed for the uncarbonated mortars (the conservative solutions).

In order to determine the potential for binder loss from uncarbonated hydraulic limes and its effect on properties and performance, Forster et al. [8] presented several test results and determined the rate of portlandite ($Ca(OH)_2$) leaching in a range of uncarbonated hydraulic lime mortars, using ammonium nitrate, and assessed the effect on strength and moisture handling characteristics. The chemical and physical properties of the NHL binders are presented in Table 2. Mortars were prepared at a constant binder to aggregate ratio of 1:3 (by volume) and with a well graded siliceous sand.

Table 2 - Chemical and physical properties of the NHL binders [8].

Binder	**Bulk density (kg/m3)**	**Mineralogical composition (%)**							
		$CaCO_2$, unburnt	Insoluble	Free $Ca(OH)_2$	Compound				
					C2S	C3A	C2AS	C4AF	CaSO4
NHL2	550	13	8	58	17	0,4	0,8	0,4	0,5
NHL3.5	620	25	9,6	25	35	0,5	1	0,5	0,8
NHL5	750	23	5,6	22	43	0,7	1,7	0,7	0,7

Assuming that the leaching process is diffusion controlled, taking into account the kinetics of $Ca(OH)_2$ leaching, the leached depth h is proportional to the square root of time, according to equation 1.

$$h = kt^{1/2} \quad (1)$$

In Eq. 1 *h* is the leaching depth (mm), *k* (mm/day½) is an index of resistance to leaching and is a materials parameter depending on the composition of the material and the chemical environment and *t* is the time in days.

The results for the leaching tests of uncarbonated NHL2, NHL3.5 and NHL5 mortars are presented in Table 3. According to [8] it was assumed an acceleration factor of 20 for the leaching tests.

Table 3 - Resistance to leaching for uncarbonated NHL2, NHL3.5 and NHL5 mortars [8].

Mortar	k (mm/day½)
NHL 2	0,16
NHL 3.5	0,14
NHL 5	0,12

The results suggest that NHL5 (eminently hydraulic) presents the highest resistance to leaching and NHL2 (feebly hydraulic) has the lowest resistance.

Regarding the leaching effect in historic heritage, the assumption made was that mortar compositions must be made with the objective to achieve a service life of 100 years (for instance) and, in order to select the best re-pointing solution using one of those NHL mortars, a probabilistic analysis is carried out using the statistical parameters of the involved variables: mean values and standard deviation with their distribution laws. For re-pointing of the joints, 3 different mortars were studied: NHL2, NHL3.5 and NHL5. For each studied mortar, the probability of reaching a leaching depth of 10 mm, 30 mm or 50 mm was calculated as a function of the mortar service life, assuming that k presents a lognormal distribution with a CoV (coefficient of variation) equal to 20%, as the majority of construction materials physical characteristics.

The conceptual basis of a probabilistic-based approach is to ensure that the required performance - controlling the leaching depth to ensure higher masonry durability and safety - is improved throughout the intended mortar and building hygrothermal behaviour. For the implementation of performance-based indicators methods, the limits must be established. However, there is no currently definition of what could be the maximum probability of failure for the problem mentioned here. Therefore, the Monte Carlo technique was implemented by assigning a probability distribution to each input parameter under consideration. For all parameters, values from within their probability distribution are randomly selected and a simulation undertaken. Simulations are undertaken repeatedly with new values randomly selected. The implementation of the cited method was carried out with 100000 generated values for each random variable.

The definition of the limit state function g(x) was used for the implementation of Monte Carlo method. Generally, the probability of failure may be expressed as the probability that the limit state function is negative: $Pf=P[g(x)<0]$.

$$g(x) = t_L - t_g = \frac{\left(\frac{h}{k}\right)^2}{365} - 100 \quad (2)$$

In eq. 2, *h* is the leaching depth (mm), *k* (mm/day½) is the index of resistance to leaching, t_L is the design life time of each mortar in years and t_g is equal to 100 years (the target value).

No explicit target performance measures are available to help to select the best retrofitting solution. Based on this, the performance-based approach and its relationship with the calculation of the design lifetime of the mortars for retrofitting masonry structures was based on reliability criteria established by Eurocode 0 (EN 1990 2002). In this code, three reliability classes are defined – RC1, RC2 and RC3 – relating to the importance of a certain structure/construction considered in terms of consequences due to failure. Each class is represented by a maximum probability of failure (Pf) which takes into account the statistical scattering in action effects, the uncertainties in resistances and the uncertainties of the chosen model. Therefore, the team decided to carry out the analysis for the most demanding reliability class, RC3, related to structures of high social and economic impact, whose limit sets a failure probability of Pf = 2.3%.

The following figures present the probabilistic calculus of the design service life of NHL2, NHL3.5 and NHL5 mortars for a leaching depth of 10mm, 30mm or 50mm (Figures 8-10).

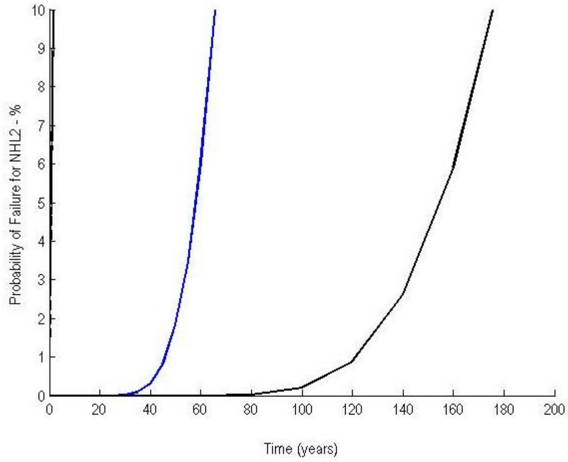


Figure 8 - Design service life of NHL2 for a leaching depth of 10 mm (left side, almost superimposed with Y-axis), 30 mm (middle) and 50 mm (right side).

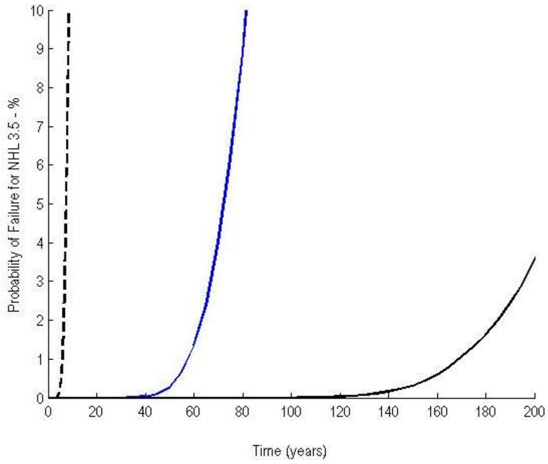


Figure 9 - Design service life of NHL3.5 for a leaching depth of 10 mm (left side), 30 mm (middle) and 50 mm (right side).

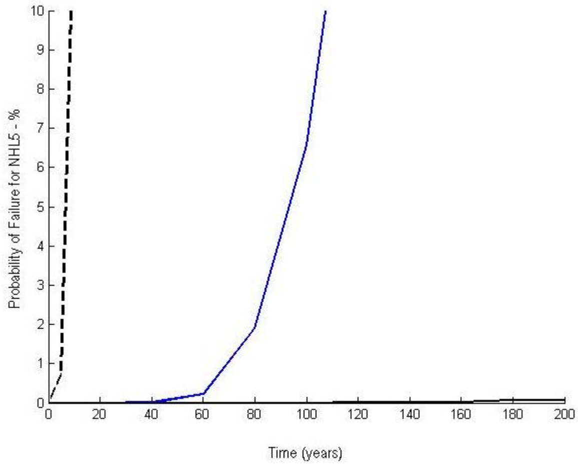


Figure 10 - Design service life of NHL5 for a leaching depth of 10 mm (left side), 30 mm (middle) and 50 mm (right side, almost superimposed with X-axis).

The previous results demonstrate that NHL5 mortars present enhanced performance when compared to NHL2 or NHL3.5 mortars. From Figs. 8–10 it can be seen that there are significant differences for each mortar composition if the effect of leaching is regarded. Considering the same level of probability of failure Pf, there is an increase in the design service life values for NHL5. However, if the leaching depth is of 30 mm none of the tested mortars present a service life higher than 80 years for a Pf = 2.3%. For this probability of failure the optimum selection is a NHL5 mortar since it is expected to present a service life higher than 100 years - assuming that a leaching depth equal to 50 mm does not compromise the safety level of the masonry structure. This behaviour is explained by the fact that the binder components vulnerable to dissolution are portlandite and calcite, and less hydraulic lime binders such as NHL2 are more susceptible to dissolution, particularly in saturated conditions. Nevertheless, if the maximum acceptable leaching depth is higher than 30mm, a mortar service life of 50 years is a reasonable value.

Although NHL5 is the best mortar for resisting leaching, it may not always be appropriate to use a high hydraulicity binder especially with a weak substrate or soft masonry units since it would cause accelerated deterioration in the host materials.

5. Hygrothermal performance evaluation of the University of the Third Age (U3A) area

Major issues such as the high level of relative humidity inside the building and the leaching phenomenon of the mortar joints between bricks masonry were taken into account as a potential degradation causes in the convent. Therefore, the paper also discusses humidity effects to historic internal environments and uses a novel probabilistic approach for evaluating performance and select the best retrofitting solutions.

As mentioned before, part of the ground floor of the convent will be used by the University of the Third Age (U3A) organization. However, the relative humidity of the future U3A zone was too high (Figure 11), enhancing the need of a hygrothermal performance evaluation in order to ensure that comfort conditions will be satisfied by empowering a suitable internal retrofitting solution and an adequate ventilation.

Figure 11 present the variation of hygrothermal conditions inside and outside the U3A zone during the *in situ* monitoring campaign with a thermo hygrometer. Figure 12 presents the hygrothermal behaviour inside the U3A zone during a spring day.

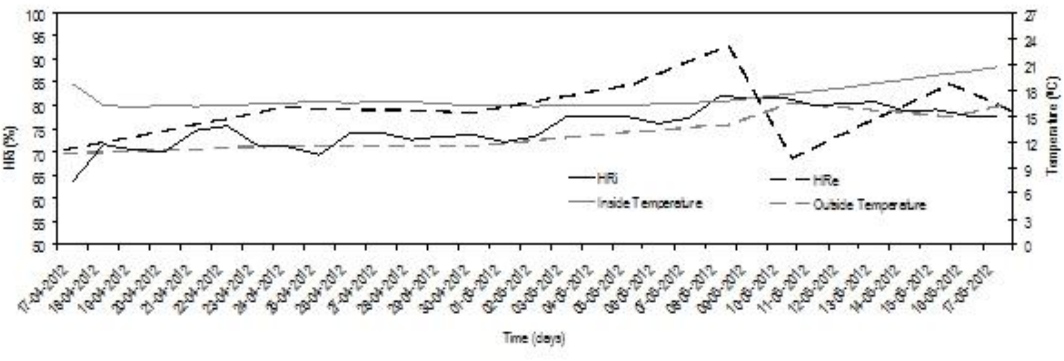


Figure 11 - Variations of outdoor and indoor temperature (air temperature) and RH at the convent zone U3A (from April 2012 to May 2012).

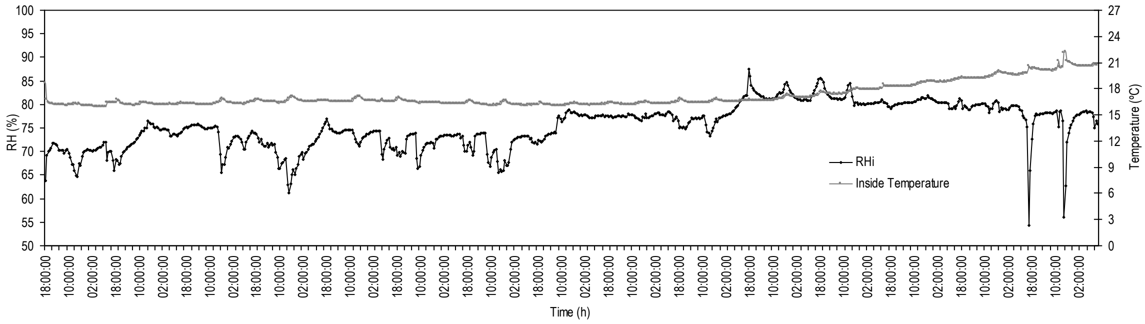


Figure 12 - Variations of indoor temperature (air temperature) and RH at the convent zone U3A during a spring day.

According to the previous results of hygrothermal conditions outdoor and indoor the future U3A zone, it is possible to observe that:

- The indoor temperature is higher than 16ºC and lower than 22ºC;
- The outdoor temperature is higher than 9ºC and lower than 33ºC;
- The indoor RH is higher than 60% and lower than 90%.

The indoor thermal daily amplitude is not higher than 3ºC (which is associated with a good thermal inertia of the building) and the daily variation of RH in the U3A zone presents values between 6% and 25% (except in two days of May) (Figure 13).

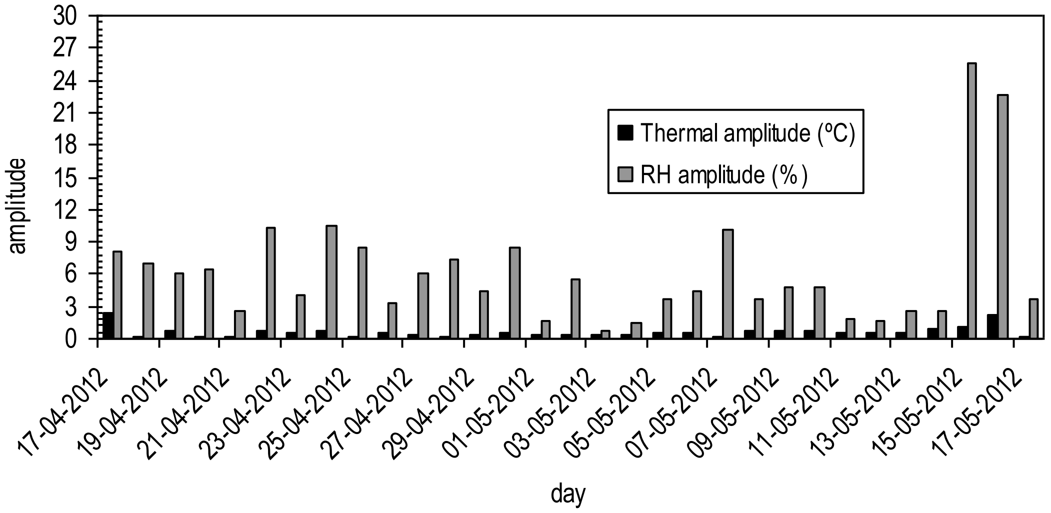


Figure 13 - Daily amplitude variation of indoor temperature and RH at the convent zone U3A (from April 2012 to May 2012).

Historic buildings like this convent are usually made of solid masonry walls and single glazed wooden windows (Figure 14). The rehabilitation of this kind of old buildings requires an upgrading of the shell so that comfortable temperatures and relative humidity can be maintained to keep up with modern life requirements.

Existing requirements for comfort, both on building regulations and working place orders, and on sustainability assessment methods, refer to the maintenance of certain levels of comfort parameters (such as air temperature, mean radiant temperature, air velocity, relative humidity). However, the level of comfort to be required for sustainable buildings is still not well defined, apart from the obvious fact that certain hygrothermal conditions should be ensured, as they can affect health of inhabitants. For example World Health Organization (WHO) guidelines and ongoing discussion on health effects of temperatures [39-41] could be taken as a reference value [24, 42].

Figure 14 - Detail view from the interior showing the wood window and the thickness of exterior walls.

The previous obtained indoor temperature results are very similar to the required values taking into account the Portuguese regulation concerning thermal comfort [43]. However, thermal performance of the convent in the U3A zone could be improved simply by using double glazing windows or using a plaster on the indoor wall surface with better hygrothermal characteristics.

Concerning the relative humidity, it is expressively high (Figure 11) and can probably affect occupants health. According to the interviews to the person in charge of the building, natural ventilation only occurs using the access door and by inefficient sealing of the old windows, since these ones are in poor operating conditions. The eventual replacement of the old windows by new ones, more airtight, will reduce natural ventilation, what, under determined values, can also be negative for inhabitants health.
The control of humidity values are accomplished through the operation of a portable dehumidification device for periods of 8h (between 9h30 am and 5h30 pm), with a capacity of 10 l / 24 h (30 ºC / 80% RH) and a storage tank inside with a capacity to 1.9 l. However, the device was not operating during the testing period.

Based on the results presented in Figures 11 -13, the use of bio based earth plasters (formulated with clayish earth, sand and vegetal fibres) can be a solution to implement inside the U3A area, due to their hygroscopic characteristics. In order to maintain a healthy indoor air quality inside the class rooms, the use of these type of bio-based materials should be promoted since they contribute to the stabilisation of fluctuations in relative humidity [44 - 46]. Nevertheless, susceptibility to biological development with the indoor conditions should also be studied and, if needed, controlled.

Humidity buffering is a desirable property of a material to absorb water vapour from the air, when relative humidity is high, and release this water as vapour when relative humidity falls. This property can be quantified using the experimentally-determined moisture buffer value (MBV). MBV indicates the amount of moisture uptaken or released by a material when it is exposed to repeated daily variations in relative humidity between two given levels (high humidity followed by a low humidity environment). The moisture buffer values of the materials are classified in to following categories: Negligible (MBV: 0.0-0.2), Limited (MBV: 0.2-0.5), Moderate (MBV: 0.5-1.0), Good (MBV: 1.0-2.0), Excellent (MBV: 2.0-upwards) [47].

Figure 15 presents several Moisture Buffer Value collected from the existing state of the art regarding bio-based materials [46; 48-50]. Taking into consideration the previous range, those MBV are in general good or excellent.

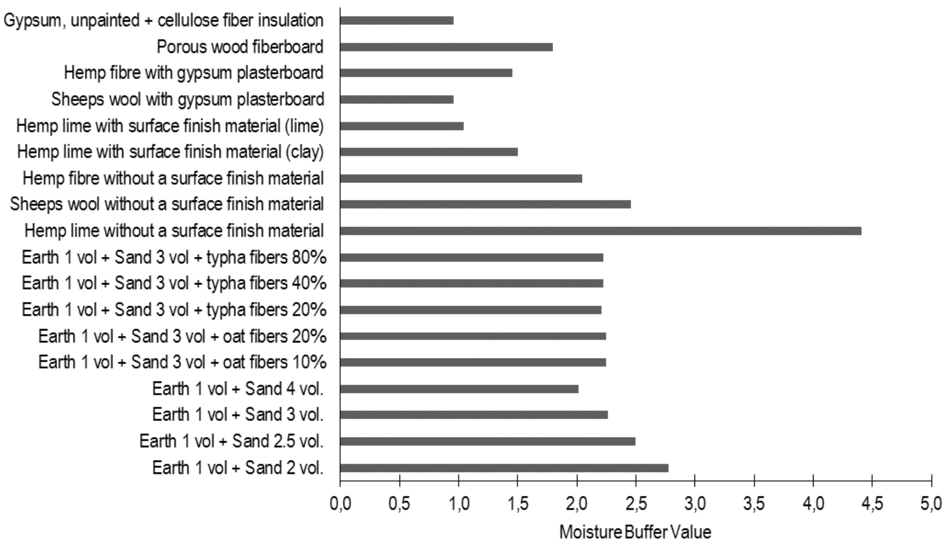


Figure 15 - Several Moisture Buffer Value collected from the existing state of the art regarding bio-based materials [46; 48-50].

Taking into account the predicted type of occupancy (a classroom between 33 and 64 m^2, as a function of the number of people in the classroom) and the type of possible solutions for the indoor rendering of the U3A area (a surface with MBV between 1 and 3), a probabilistic analysis is carried out to optimise the ventilation and RH control. This was made using the statistical parameters of the involved variables: mean values and standard deviation with their distribution laws. The mean values and standard deviation of each variable are based on the experimental values obtained by the authors and on [44- 50] (Table 4).

Table 4 – Calculus variables.

Variable	a	b	Distribution
Room conditions			
Floor area (m^2)	33	64	U (a,b)
Number of people in the classroom	5	15	U (a,b)
Indoor temperature (ºC)	18	0.15a	N (a,b)
MBV	a	0.2a	N (a,b)

Notation: U (a,b) = Uniform distribution between a and b; N (a,b) = Normal distribution with mean value a and standard deviation b.

In order to optimise the ventilation and RH control inside the U3A by taking into account the moisture buffer capacity of different rendering solutions, a new limit for the state function (g_{U3A} (x)) was defined. It takes into account that the critical indoor relative humidity occurs at 70%. The simulations are undertaken repeatedly with new values randomly selected. The implementation of the cited method was carried out by means of the Monte Carlo method with 1000000 generated values for each random variable.

The definition of the limit state function g(x) was used for the implementation of Monte Carlo method. Generally, the probability of failure (Pf) may be expresses as the probability that the limit state function is negative: Pf=P[g(x)<0].

$$g_{U3A}(x) = 70 - \frac{w \times \mathrm{P} \times x}{MBV_{rendering} \times A_{wall} + MBV_{air} \times V} \quad (3)$$

In eq. 3, w (50 g/l) is the water vapour produced by one person in a classroom, P is the number of people inside the classroom, x (h) is the number of hours each person is inside the classroom, $MBV_{rendering}$ (g/(m^2·%RH)), is the moisture buffer value of the rendering applied in the surface of the interior wall, A_{wall} is the area of the indoor wall surface (m^2), V is the classroom volume (m^3) and MBV_{air} (0,20g/(m^3·%RH)), is the moisture buffer value of the air inside the classroom.

Once again, no explicit target performance measures are available to help to select the best retrofitting solution. Therefore, it was decided to carry out the analysis for the number of hours inside a non-ventilated classroom as a function of the number of people inside the U3A for different types of rendering applied in the surface (MBV=1, 2 and 3) (Figure 16).

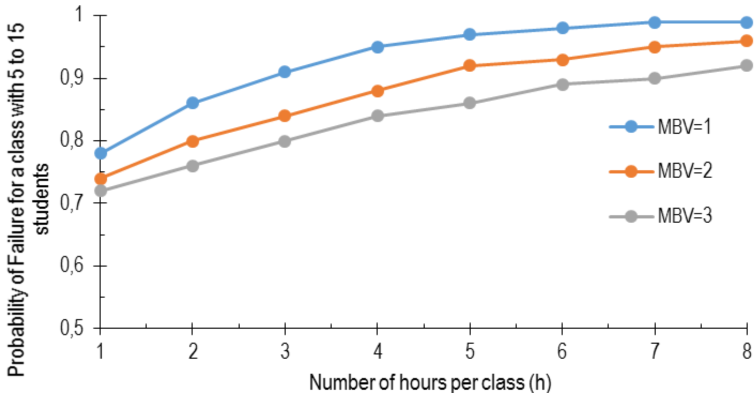


Figure 16 – Probability of reaching a relative humidity level higher than 70% for a classroom with 5 to 15 students, if the surface is retrofitted with materials with MBV=1, 2 or 3.

.
The previous results show that by increasing the MBV of the retrofitting solution, the Pf decreases 10% (from MBV=1 to 3) if the number of hours per class in not higher than 4-5 h. However, this is not enough and some natural ventilation recommendation must be implemented. Therefore it is suggested that the number of hours per class with closed door and windows should not be higher than 2h, so that the air could circulate after that period.
Since the highest RH values at the U3A zone do not satisfy the minimum values to promote a healthy environment, the authors suggest a careful scheduling of operation of heating and dehumidification systems devices.

6. Conclusions

This paper presents the diagnosis and some retrofitting solutions for the presented pathology in the convent of Madre de Deus of Verderena, Barreiro, Portugal, enhanced by previous construction works. Particular emphasis is given to the modification of the ground floor of the convent that will be used by the University of the Third Age (U3A) organization. In this context, a repair solution of the building should be built up on actions that would simultaneously improve the interior hygrothermal comfort and prevent water infiltration damages. The design and selection of a retrofitting solution has been carried out through performance-based methods (according to constructive materials behaviour, hygrothermal and occupants' behaviour and climatic conditions) as an alternative to the deem-to-satisfy approach. The corresponding conclusions are presented as follows:

1) To re-establish the integrity of the envelope taking into account comfort, structural issues and aesthetics. In this sense, internal and external paints and cement-based render should be removed. New rendering could be executed with mortars compatible with old masonry after proper in situ testing. Correction of the terrace floor slope and of the water proofing system, minimising the water ingress and consequent leaching phenomena in the masonry vault.

2) Since the convent is subjected to leaching phenomena and structural integrity of masonry may be a function of that, it was necessary to find the best repointing solution, compatible with the existing masonry materials. Therefore, 3 different natural hydraulic lime mortars (NHL2, NHL3.5 and NHL5) were analysed.

3) For each studied mortar, the probability of reaching a leaching depth of 10 mm, 30 mm or 50 mm was calculated as a function of the mortar service life. The results demonstrate that NHL5 mortars present enhanced performance when compared to NHL2 or NHL3.5 mortars. As soon as the maximum acceptable leaching depth is higher than 30mm, a mortar service life of 50 years is a reasonable value. Therefore, NHL5 mortar is the indicated solution taking into account the expected saturated conditions in the building fabrics due to climatic changes.

4) Hygrothermal performance evaluation of the future University of the Third Age space was studied in order to ensure that comfort conditions will be satisfied by empowering a suitable internal retrofitting solution and an adequate ventilation. Due to their hygrothermal characteristics, namely the humidity buffering values, the use of eco-efficient hygroscopic earth plasters (bio-based materials) can be a solution to implement inside the U3A.

5) Taking into account the predicted type of occupancy and the type of possible solutions for the indoor plastering of the U3A area, a probabilistic analysis was carried out to optimise the ventilation and RH control. The results show that by increasing the MBV of the retrofitting solution, the probability of failure decreases 10% (from MBV=1 to 3). However, this is not enough and some natural ventilation recommendation must be defined and implemented. Therefore it is suggested that the number of hours per class with closed door and windows should not be higher than 2h. The recommendation also includes a careful scheduling of operation of heating and dehumidification systems devices.

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